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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

MEASURING INFORMATION GAIN IN THE OBJECTIVE FORCE

by

Joseph A. Baird

June 2003

Thesis Advisor:	Eugene P. Paulo
Thesis Co-Advisor	Alvin F. Crowder
Second Reader:	Susan M. Sanchez

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Many researchers are attempting to quantify or understand the value of information, especially for the Army as it enters its transformation. Information can be decomposed into various qualities. Three of these qualities, timeliness, accuracy, and completeness, form the basis for this thesis. This thesis uses a simulation framework developed by the author to analyze the three components of information listed above. The scenario selected is a typical vignette of an Objective Force company-sized element conducting offensive operations against threat elements. Knowledge of the threat was compromised by the presence of decoy elements as well as previously damaged or killed systems (BDA). In this scenario the fires are initiated from standoff ranges. The initial and running assessments of the threat composition are made based on the information provided by sensors on board the unit's organic unmanned aerial vehicles (UAVs). Analysis of the simulation results helps in understanding how components of information quality affect the overall effectiveness of the force as reflected in an efficiency measure. Additionally, critical thresholds for accuracy, completeness, and timeliness of information are pinpointed to inform Objective Force decision makers.

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MEASURING INFORMATION GAIN IN THE OBJECTIVE FORCE

Joseph A. Baird
Major, United States Army
B.S., Wheaton College, 1992

Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
June 2003

Author: Joseph A. Baird

Approved by: Eugene P. Paulo
Thesis Advisor

Alvin F. Crowder
Thesis Co-Advisor

Susan M. Sanchez
Second Reader

James N. Eagle
Chairman, Department of Operations Research

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ABSTRACT

Many researchers are attempting to quantify or understand the value of information, especially for the Army as it enters its transformation. Information can be decomposed into various qualities. Three of these qualities, timeliness, accuracy, and completeness, form the basis for this thesis. This thesis uses a simulation framework developed by the author to analyze the three components of information listed above. The scenario selected is a typical vignette of an Objective Force company-sized element conducting offensive operations against threat elements. Knowledge of the threat was compromised by the presence of decoy elements as well as previously damaged or killed systems (BDA). In this scenario the fires are initiated from standoff ranges. The initial and running assessments of the threat composition are made based on the information provided by sensors on board the unit's organic unmanned aerial vehicles (UAVs). Analysis of the simulation results helps in understanding how components of information quality affect the overall effectiveness of the force as reflected in an efficiency measure. Additionally, critical thresholds for timeliness, accuracy, and completeness of information are pinpointed to inform Objective Force decision makers.

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EXECUTIVE SUMMARY

The US Army and its Training and Doctrine Command have taken on the responsibility for determining how to trade heavy caliber weapons and heavy armor for lighter, more agile, and information-dependent fighting systems. Understanding the impact of how information enables the future Objective Force is critical in this high-risk endeavor. A common criticism of information-based warfare is, “You can’t know an enemy to death.”

There is a difference between the value and the quality of information. Value is subjective and depends on the decision maker as well as his information needs. Battle command analysis focuses on information value to different levels of information users. Information quality is more objective and is the focus of this research.

Information quality is defined by its timeliness, accuracy and completeness.[1] The overarching problem examined by this research is determining the relative influence these components of information quality have on combat outcomes.

The methodology used to explore this problem consists of two major pieces. The first step is the development of a simulation framework that models an Objective Force unit engaged in combat operations. A Mounted Combat System (MCS) Company, one of the Unit of Action (UA) sub-elements, is the subject of the simulation tool. The MCS Company is optimized for extended line of sight (LOS) with beyond line of sight (BLOS) fires, and employs chemical energy (CE) and

[1] Perry, p. 30

kinetic energy (KE) munitions to engage at standoff.[2] Its mission in the simulation model is to identify and eliminate enemy targets dispersed throughout an objective area using organic fires at standoff ranges. The future threat, recognizing its overmatch by Objective Force units, will use adaptive tactics, deception, and physical decoys to their own advantage. The simulation tool mirrors this operational environment with its ability to model decoys, stationary and moving live targets, and battlefield clutter in the form of battle damaged vehicles. The simulation also models the three organic Unmanned Aerial Vehicles (UAV CL II) that are used to provide the BDA and target location data.

The second step is performing statistical analysis on the simulation output. This facilitates making observations about information quality component relationships and how they impact force effectiveness as reflected in an efficiency measure. A 3^3 full factorial designed experiment is used to structure the simulation responses by looking at timeliness, accuracy, and completeness each at three levels. The response for each design point of the experiment is the number of rounds required to eliminate a pre-determined percentage of enemy targets. Analysis of variance, polynomial regression and data correlation are used to make broad observations about the dynamics of these information quality components.

The results of this study show that timeliness, accuracy, and completeness are significant in influencing the measure of effectiveness, but there is a difference in

[2] TRADOC Pamphlet 525-3-90/O&O, p. 3-23

their relative importance with regard to how much of the variability in the response each component can explain. In this scenario, the completeness factor explains 31% of the variability while accuracy and timeliness explain 23% and 12% respectively. Completeness stands out with respect to the importance of a single factor.

Additionally, some components produce accelerated changes in the MOE compared to the degree of change in the level of the factor. Increasing the timeliness factor level from medium to high results in tremendous improvements in efficiency while a change from medium to low results in only a small decrease in efficiency. However, increasing the completeness factor level from medium to high results in a mild increase in efficiency while a change from medium to low results in a significantly large decrease in efficiency.

Finally, there is a synergistic effect when the combination of timeliness and accuracy are held at their high levels. Three of the top five simulation run responses occur when this is the case. Timeliness and accuracy combine in a way that is resilient to the effect of completeness.

These dynamics are certainly scenario specific, but this study demonstrates that they do exist and provides a methodology and framework with which to discover them. This information in the hands of a concept developer allows him to make wise choices in determining what technologies and tactics are needed to improve the success of units optimized for specific missions.

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I. INTRODUCTION

A. BACKGROUND

The U.S. Army's new Objective Force design calls for a new paradigm in fighting our future battles. Objective Force units are anticipated to have the capability to "see first, understand first, act first and finish decisively."[3] The key to making this concept a reality is an overwhelming situational understanding largely made possible by the ability to obtain, process and rapidly move an abundance of information on the future battlefield.

The traditional elements of combat power include Maneuver, Firepower, Protection and Leadership resulting in the formula: CP=M+F+P+L. According to Army concept developers, however, it is envisioned that in Objective Force units a "situational understanding derived from real-time, accurate Information raises combat power exponentially: $CP=(M+F+P+L)^{Information}$."[4]

One example of the impact of information, consistent with the idea expressed in the above formula, is an observation by VADM(ret.) Cebrowski in Transformation Trends: "The air force says that a target once requiring 1,000 bombs to destroy now requires only one. That magnitude of change is owed almost entirely to information technology and processes."[5]

---

[3] TRADOC Pamphlet 525-3-90/O&O, p. 4-3

[4] TRADOC Pamphlet 525-3-90/O&O, p. 3-1

[5] Cebrowski, p. 2

B. PROBLEM

In this day and age there is a lot of emphasis on the merits of information, and much effort is going into how it can be obtained more quickly, completely and accurately. However, "little has been done to establish a clear relationship between information and the outcome of military operations."[6] The first step in attempting to discern what this relationship looks like is defining what is meant by the term *information*.

According to Dr. Walter L. Perry in his article, "Knowledge and Combat Outcomes," information has two main attributes: value and quality.[7] Information has value if it informs the commander and answers questions posed by his intelligence requirements such as Priority Intelligence Requirements (PIR) or Commanders Critical Information Requirements (CCIR). In other words, valuable information is relevant to the situation at hand.

The quality of information, however, depends on its accuracy, timeliness and completeness.[8] Valuable information may not always be of high quality. On the other hand, information could have high quality but have no relevance to the situation at hand, and therefore have little to no value.

The purpose of this thesis is to investigate the impact of information on Objective Force operations. The focus will be on information quality, as defined by Perry above, and the goal is to draw some broad conclusions about

[6] Darilek, p. 2

[7] Perry, p. 30

[8] Perry, p. 30

how the individual components of information quality can influence combat outcomes.

A specific analysis of information timeliness, accuracy, and completeness and their impact on a combat scenario does not yet exist. These three terms were discussed in a Joint Battle Damage Assessment Joint Feasibility Study Report in September 2000.[9] However, in this report they were used as measures of effectiveness to evaluate mobile target vs. fixed target battle damage assessment (BDA) processes, not inputs to the problem.

C. METHODOLOGY

Under the Objective Force concept, the Unit of Action (UA) takes on a role similar to that of the traditional maneuver brigade. There are many critical tasks that must be done with a high level of precision by the UA, such as firing and maneuvering under contact, delivering fires at standoff, and assuring mobility near the objective.[10] An additional critical task is tracking and evaluating Battle Damage Assessment (BDA). Accurate BDA facilitates at least two things: (1) decisive action by the commander so he knows when he can transition to subsequent actions and maintain pressure on the enemy, and (2) efficient expenditure of limited munitions.[11]

For this thesis, a simulation model called the Mounted Combat System Killing Machine (MCSKM) was developed. The simulation treats BDA, target type and target location as the types of information under observation. With a focus

[9] Joint Battle Damage Assessment Feasibility Report, p. 2-3

[10] TRADOC Pamphlet 525-3-90/O&O, p. 4-4

[11] TRADOC Pamphlet 525-3-90/O&O, p. 4-13

on efficient expenditure of munitions, the model measures the impact of this information gain on the results of a specific scenario.

A Mounted Combat System (MCS) Company, one of the UA sub-elements, is the subject of the simulation. It is optimized for extended line of sight (LOS) with beyond line of sight (BLOS) fires, and employs chemical energy (CE) and kinetic energy (KE) munitions to engage at standoff.[12] Its mission in the simulation model is to identify and eliminate targets dispersed throughout an objective area using organic fires at standoff ranges. The MCS Company has a total of 10 MCS weapon platforms available to engage targets as shown in figure 1 below. This unit also has three organic Unmanned Aerial Vehicles (UAV CL II) that are part of its table of organization and equipment (TOE) as shown in figure 2 below. These UAVs are used to provide the BDA and target location data.

[12] TRADOC Pamphlet 525-3-90/O&O, p. 3-23

Mounted Combat System Company

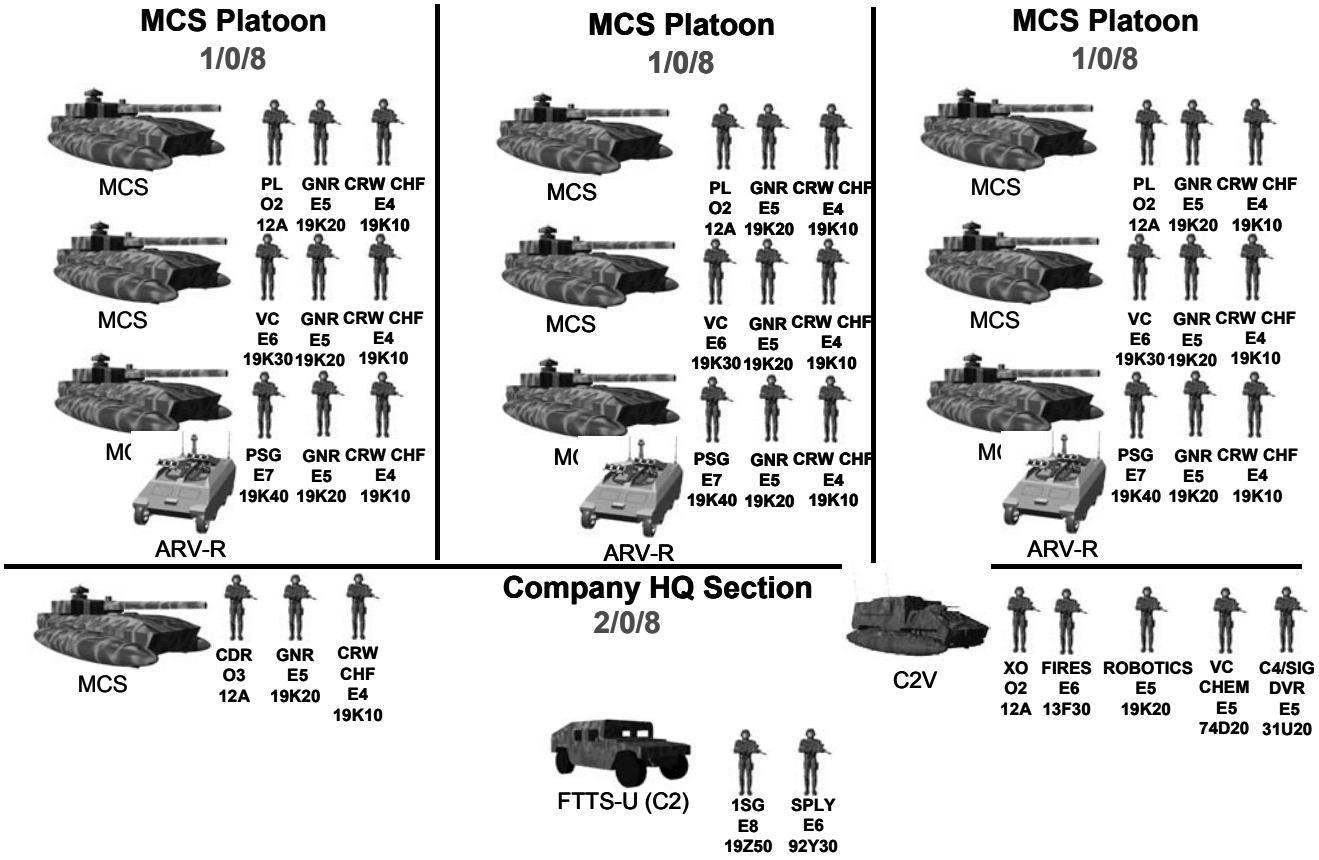

Figure 1. MCS Company Equipment

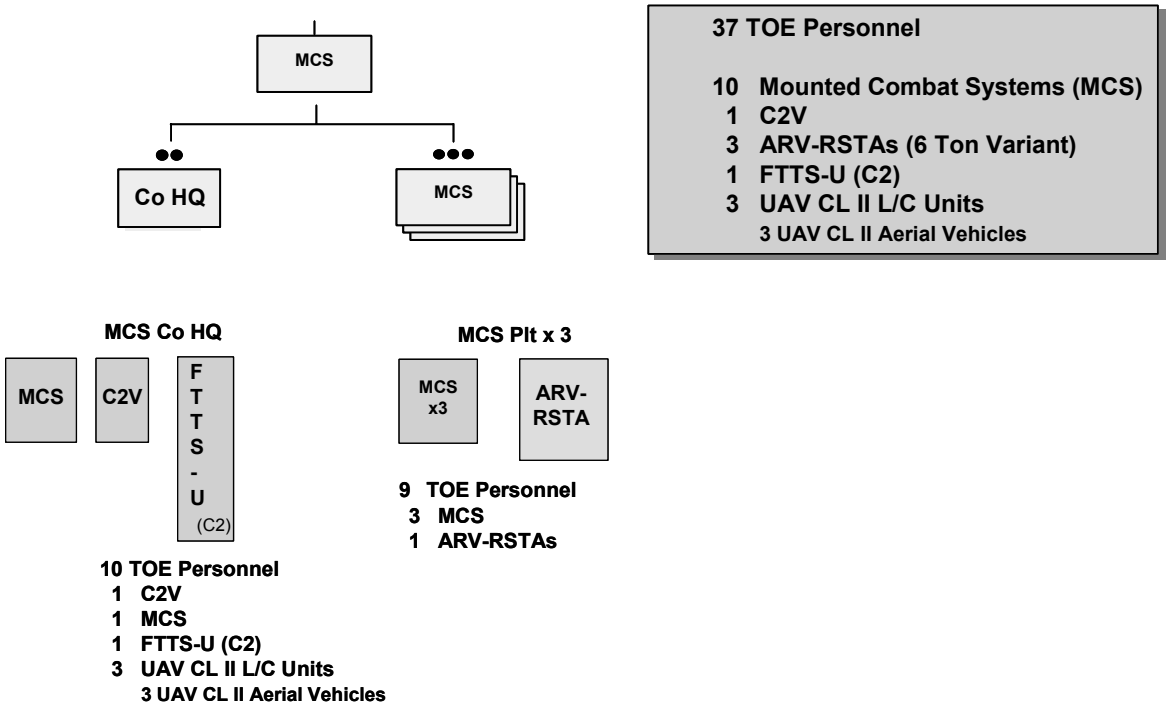

Figure 2. MCS Company Organization

The components of timeliness, accuracy and completeness of the information captured on the ground are varied and the resulting impact on the number of munitions it takes to eliminate a certain percentage of the live targets is measured. Listed below are the definitions of these information quality components and how they are represented in the MCSKM.

1. Timeliness

Timeliness reflects the relationship between the age of an information item and the tasks or missions it must

support.[13] In the MCSKM, the timeliness factor represents the amount of time it takes from the detection of a target to the impact of a round on the target. The processes imbedded in this factor are the UAV data transmission time, man/machine image processing time, firing decision time and the round time of flight. Essentially this is the time it takes for raw data to become actionable information combined with the time to complete the resulting action.

2. Accuracy

Accuracy is a measure of how faithfully the items of information represent the realities they describe.[14] In the MCSKM, accuracy is represented by the conditional probability of classification given that one of the three battlefield entities is present. This is the probability that a live target, dead target or decoy will be classified as such given that it was detected. In the MCSKM, if an entity is present in the area being searched it will be detected with a probability of 1.0 for the sake of simplicity. Therefore, accuracy is purely a function of the quality of the classification process.

3. Completeness

Completeness describes the level to which all the relevant items of information are available including entities (such as targets), attributes (such as movement) and the relationships between them.[15] In the MCSKM, the amount of area on the ground a UAV can observe and evaluate for the presence of targets in a given unit of time represents completeness of information.

[13] Alberts, p. 85

[14] Alberts, p. 84

[15] Alberts, p. 84

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II. MODEL DEVELOPMENT

A. SCENARIO

The objective area for the MCSKM scenario is an 8 kilometer by 8 kilometer box of primarily open, rolling terrain. The MCS Company is located in an attack by fire position and, with standoff range firing capability, destroys targets in the targeted area of interest (TAI) in support of a follow-on assault by an adjacent infantry company.

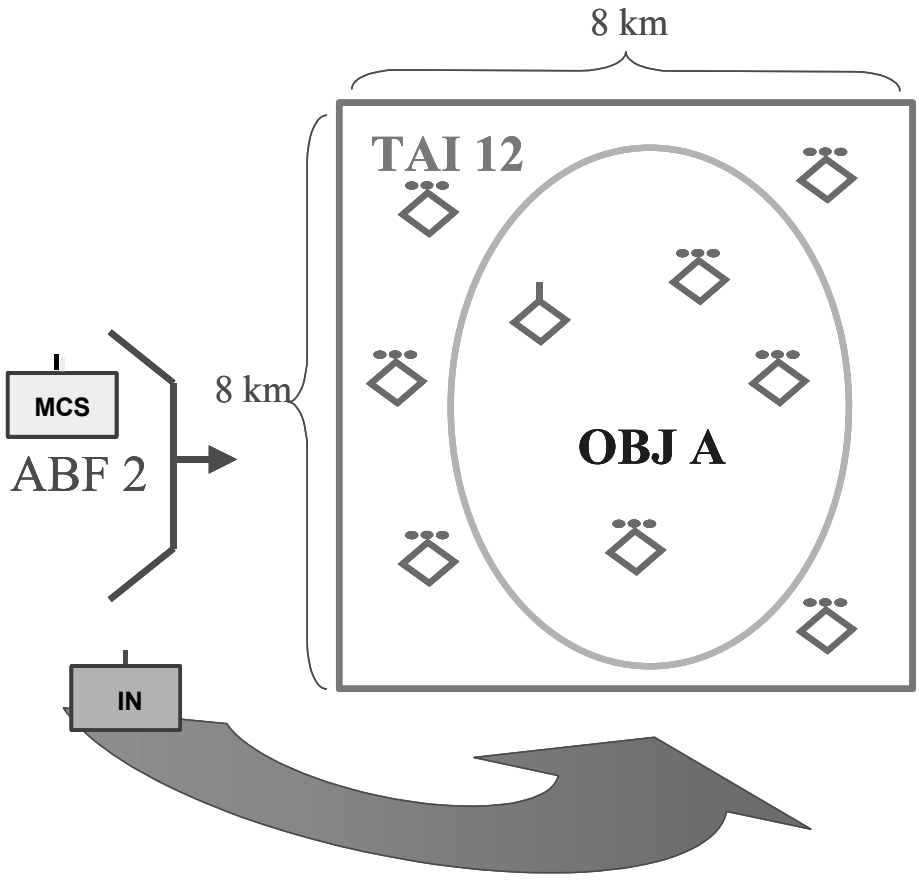


Figure 3. Scenario Environment

Targets are randomly and uniformly dispersed throughout the objective area. There are 50 total targets

and they are broken down into three types with the following distribution: 36 live, 7 dead and 7 decoy. Half of the live targets are specified as movers and will move randomly until killed by a munition fired from an MCS weapon platform. Stationary targets represent systems conducting a static defense, command posts, air defense assets, or other fixed sites. Dead targets are systems that are previously damaged or killed. Decoys are non-moving entities that have no military significance but can be mistaken for valid, live targets. See table 1 for target summary:

Table 1. Distribution of Target Types

Target Types	Number
Live (moving)	18
Live (stationary)	18
Dead	7
Decoy	7

Three organic UAVs fly in a random pattern and report perceived target imagery to the analysts in the command post. This target imagery serves as the sole basis for target location and target type. With this information a decision will be made to fire or not fire at a target. There are no other reconnaissance assets in the area of influence except what gets transmitted via the UAVs.

If a target is perceived as live then a decision to fire at that target is made. The end state is achieved when 80% of the live targets are destroyed. It is important to note that the values chosen for this scenario are easily modified by the user in order to explore other scenarios.

B. GENERAL MODEL

The Mounted Combat System Killing Machine (MCSKM) is a discrete-event simulation written in the JAVA programming language. The MCSKM implements the simulation tool Simkit, a discrete-event simulation package developed and maintained by Research Assistant Professor Arnold H. Buss of the Naval Postgraduate School. The objective of the MCSKM is to provide a framework to explore the information quality components of timeliness, accuracy and completeness and how these factors influence the number of munitions required to kill a certain percentage of the targets. Table 2 below shows all of the available parameter adjustments that can be made by the user. Experimentation was done with all of these settings in determining the right mix for the final experiment. These excursions will be discussed in Chapter IV. For the analysis in this thesis, the bold settings remained fixed while the remaining settings were varied in the experiment described in Chapter III.

Table 2. MCSKM Available Adjustable Parameters

	Simulation Factors	Description	Good Value	Medium Value	Low Value
Accuracy	**probability of detection**	probability of detecting a target (live, dead or decoy)	**1.0**		
	probability of false detection	probability of detecting a live target when no targets of any type are present (type II error)	**0.0**		
	probability of determination (perceived | actual)	probability of determining what a target is once detected			
		p(live | live)	0.8	0.6	0.4
		p(dead | live)	0.1	0.2	0.3
		p(decoy | live)	0.1	0.2	0.3
		p(live | dead)	0.1	0.2	0.3
		p(dead | dead)	0.8	0.6	0.4
		p(decoy | dead)	0.1	0.2	0.3
		p(live | decoy)	0.1	0.2	0.3
		p(dead | decoy)	0.1	0.2	0.3
		p(decoy | decoy)	0.8	0.6	0.6
Timeli-ness	processing time	process = UAV glimpse trasmission time + man/machine image processing time + firing decision time + round time of flight	10 sec	30 sec	60 sec
	UAV transmission interval	seconds between UAV transmissions	**5**		
Completeness	**Number of UAVs**	How many simultaneous randomly searching UAVs in the air - should be three based on the Nov 02 FCS O&O	**3**		
	box size	how much area a UAV can see in a singe glimpse (single dimension of box in meters)	400	200	100
	UAV speed	km/hr	120	60	30

bold = held fixed in simulation

The MCSKM is comprised of two basic processes: a UAV process and a shooting process. Both of these processes will be explained in detail in the next section. In general, a UAV process is instantiated (i.e., created in the software) for each UAV represented in the model. In this model there are three UAV processes in place. There is only one shooting process in place and it "listens" to each UAV process in order to track individual UAV movements and locations. Figure 4 below displays this listening relationship.

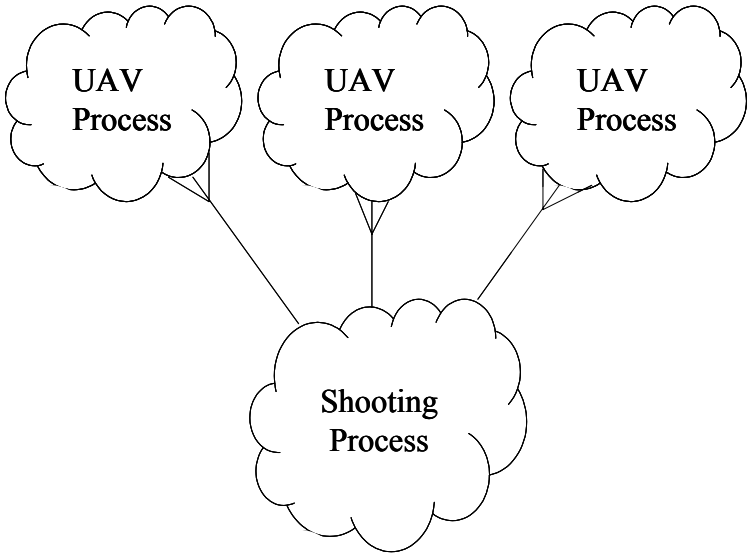


Figure 4. MCSKM Listening Scheme

While each UAV process controls the UAV movement, the shooting process does all of the real work in the model. The shooting process manages all target movements, target classifications, target state changes, firing delays and kill adjudications.

C. INITIALIZATION

At the beginning of each run of the MCSKM, all targets are given an exact grid location based on the 8 kilometers by 8 kilometers objective area. These locations are random, uniformly distributed and given in terms of meters. For example, the lower left corner of the objective area would be grid location (0.0, 0.0) and a target that is 5 kilometers to the right of the origin and 3 kilometers up would be at grid location (5000, 3000). For the 50% of the live targets that are designated as movers, they are

assigned an initial random azimuth $[0,2\pi]$ to begin movement as well.

The UAV locations are represented differently from the targets. Based on the size of the box representing how much area a UAV can see in a single glimpse, the objective area is divided up into grids of the same dimension. For example, if the box size representing how much a UAV can monitor on the ground is 400 meters by 400 meters for a given run, then the objective area is divided into a 20 by 20 grid system (8000m/400m = 20, the number of grids on each axis). Movement will be described later, but each UAV will have a random starting location in one of these grids for each run of the MCSKM. Figure 5 below demonstrates starting locations of (5, 5), (10, 15) and (18, 10) for the three UAVS as an example.

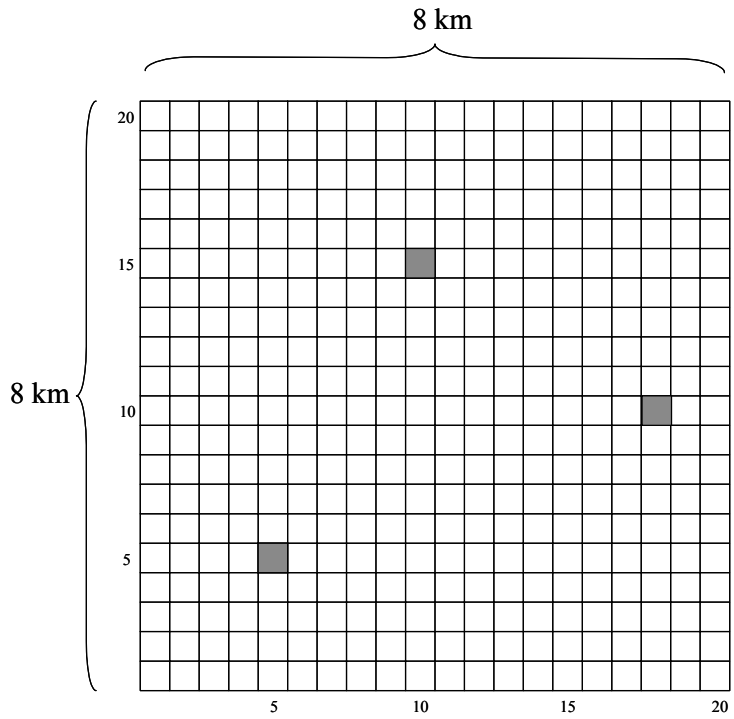


Figure 5. UAV Starting Locations in AI

D. UAV PROCESS

Movement of a single UAV is simulated by “looking” at one particular grid square for the amount of time it would take the UAV to move across the grid square in a linear fashion at a fixed speed. For example, if UAV speed = 120 km/h and the grid square is 400m x 400m then the time in grid = (400m)/(120 km/h) = 12 seconds. The choice to move from one grid square to another instead of tracing out a precise path along exact coordinates was made for the sake of simplicity in programming. To travel 400m in 12 seconds with a sensor sweep width of 400m is roughly equivalent to occupying a 400m by 400m grid square for 12 seconds. Although some precision is lost in the case of a diagonal move, it is not a great concern in light of the fact that the UAV movement is already abstracted.

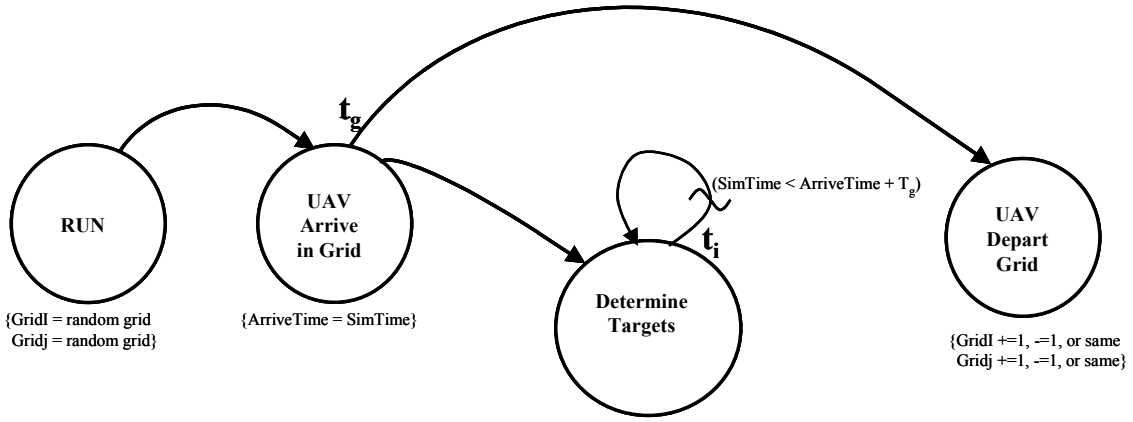
After this time has passed the UAV “moves” to an adjacent grid square in a random manner. The UAV can move into any one of the eight adjacent grid squares but it cannot remain stationary. If the UAV is on the border of the AI it is not allowed to move in any direction that would take it outside of the AI. The footprint of what the UAV can see (have the potential to detect and classify) on the ground is represented by the size of the grid square.

This is the part of the model where completeness plays its role. The size of the grid square and the speed of the UAV, in conjunction with each other, control the amount of information available per period of time. With 12 seconds time on station for any size grid square, the completeness levels are determined by the following parameter value combinations:

Table 3. Completeness Levels

	High	Medium	Low
UAV Speed	120 km/h	60 km/h	30 km/h
Grid Size	400m	200m	100m

Figure 6 below is an event graph of the UAV Process. The RUN event initializes the UAV in a random starting location and schedules the first arrival in a grid square. Upon arrival, the “UAV Depart Grid” is scheduled for when the time in the grid will have elapsed and a “Determine Targets” is scheduled immediately which is the UAV’s first attempt to detect and classify any targets present. The UAV process only signals for the “Determine Targets” event to happen; the actual work of this event is done in the shooting process and will be explained later. After arrival in the grid and taking an initial glimpse, the UAV will continue to attempt to determine targets by taking a glimpse at 5-second intervals until its time in the grid has expired. Once the time is up it will move to another grid in the manner explained above.



Parameters	State Variables
t_g – time in grid	gridI – grid number in X orientation
t_i – time between glimpses	gridJ – grid number in Y orientation
	arriveTime – time of arrival in grid

Figure 6. UAV Process Event Graph

E. SHOOTING PROCESS

The Shooting Process is initiated by any UAV Process's call for a "Determine Targets" event. The model contains variables for the probability of false detection (type II error), the probability of detection, and the conditional probability of classification given a detection. However, the probability of false detection was fixed at 0.0 and the probability of detection was fixed at 1.0 for the sake of simplicity in this implementation of the MCSKM. The reasoning for these choices is explained in chapter IV. Therefore, if a target is present it will be detected. Once detection occurs, the UAV will classify the target based on the conditional probability of

classification parameter setting. If a target is detected and classified as live, then a decision to fire is made.

The impact of the round will be delayed by a number of seconds based on the processing time parameter. This simulates the time it takes for raw data to become actionable information and then be acted upon. Once a target is identified as live and has a round fired at it, that target is not eligible for detection again until that round has landed. This prevents multiple rounds being fired at the same live target in a single grid square. Since half of the live targets are moving, there is always a chance that the original target may not be in the same grid when the round makes impact.

This process keeps iterating until a specified target attrition level is achieved. This level is variable in the MCSKM but for this analysis the attrition level is 80% of the instantiated live targets as requested by the scenario under observation. The implications of changing this threshold are discussed in chapter IV. The simulation terminates once that attrition level is met. The measure of effectiveness for a given run is the number of munitions required to reach the specified level of attrition.

Figure 7 below is an event graph of the Shooting Process. Since this is where the bulk of the simulation takes place, each event will be discussed in detail.

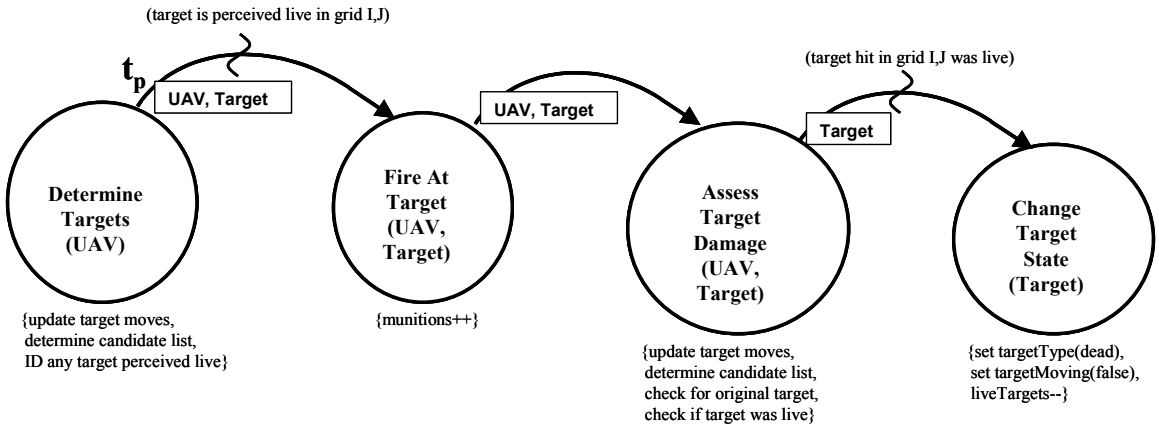

Shooting Process
(target is perceived live in grid I,J)
t_p
UAV, Target
Determine Targets (UAV)
{update target moves, determine candidate list, ID any target perceived live}
UAV, Target
Fire At Target (UAV, Target)
{munitions++}
(target hit in grid I,J was live)
Target
Assess Target Damage (UAV, Target)
{update target moves, determine candidate list, check for original target, check if target was live}
Change Target State (Target)
{set targetType(dead), set targetMoving(false), liveTargets--}
Parameters
t_p – time to process data
p_c – p(perceived|actual)
State Variables
munitions – number of MCS munitions fired
liveTargets – number of live targets remaining

Figure 7. Shooting Process Event Graph

1. "Determine Targets" Event

The "Determine Targets" event in the Shooting Process is scheduled by the "Determine Targets" event in the UAV Process. The Shooting Process knows when to conduct this event because it "listens" to the UAV Processes. The UAV Process passes its grid location so that the Shooting Process knows where to look for targets.

a. Target Movement

Since some of the live targets are movers, their locations are updated first. Moving targets move at a fixed speed for a fixed duration in a linear fashion before they stop and change direction. The speed and move duration are both variable but in this analysis they are held constant at 27 km/h and 80 seconds respectively. At the end of a target's move, a new azimuth is generated randomly and the target commences its movement. Azimuths

that will lead a target out of the objective area by the end of its move segment are not allowed. Figure 8 below shows one possibility for three consecutive target moves.

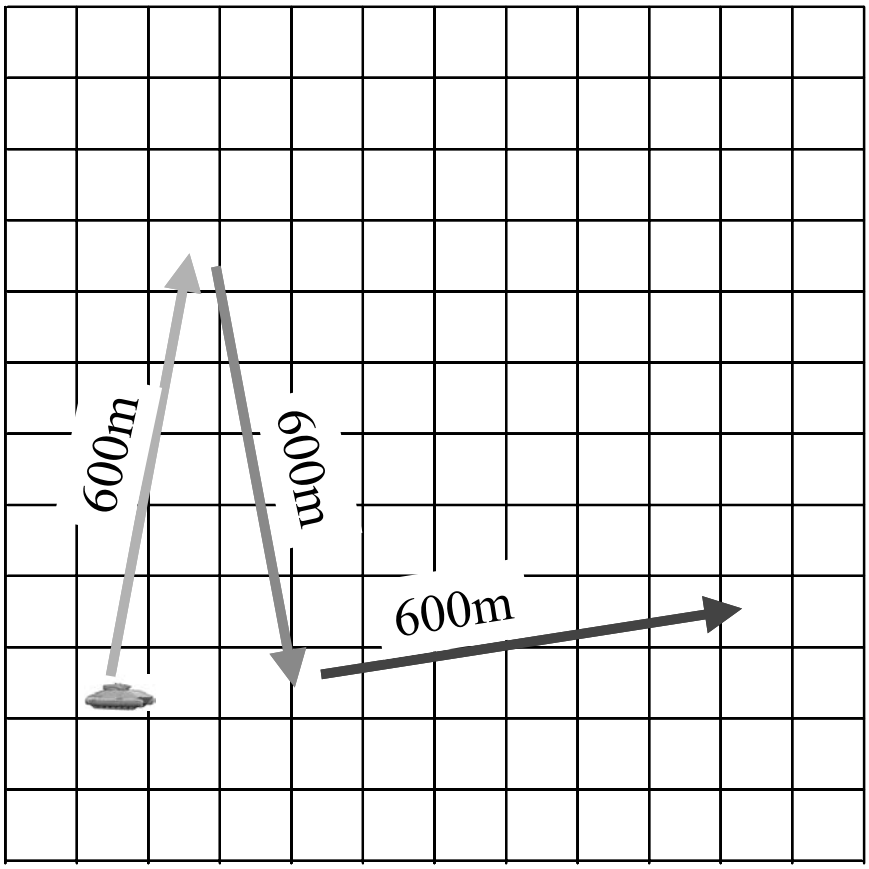


Figure 8. Target Movement Example

b. Target Classification

Once target location adjustments are made for the movers, the list of Target objects is iterated through to determine which targets are in the current grid of interest. Targets that are located in the grid are pulled from the master target list and added to a separate candidate list. The candidate list is then iterated through and each target is classified as live, dead or a

decoy based on the conditional probability of classification.

This is the part of the model where accuracy plays its role. The probability of classification given a detection directly affects the quality of a target classification. The accuracy levels are determined by the following sets of parameter settings provided by the sponsor:

Table 4. Accuracy Levels

	probability of classification (perceived | actual)	High	Medium	Low
Live	p(live | live)	0.8	0.6	0.4
	p(dead | live)	0.1	0.2	0.3
	p(decoy | live)	0.1	0.2	0.3
Dead	p(live | dead)	0.1	0.2	0.3
	p(dead | dead)	0.8	0.6	0.4
	p(decoy | dead)	0.1	0.2	0.3
Decoy	p(live | decoy)	0.1	0.2	0.3
	p(dead | decoy)	0.1	0.2	0.3
	p(decoy | decoy)	0.8	0.6	0.6

For example, if the current target under evaluation is actually dead and the p(target is perceived live|target is actually dead) = .2, then there is a 20% chance that this target will be misclassified as live. Targets that are classified as dead or decoy are returned to the master target list. However, any target that is classified as live is sent to the “Fire At Target” event as one of the parameters. The other parameter sent to the “Fire At Target” event is the location of the UAV when this target was detected and classified.

c. Target Management

Once a target is perceived (or classified) as live it does not go back into the master target list until

later in the process. The reason for this is because the same UAV will make multiple glimpses in the same grid before it moves to the next grid. If it has the opportunity to reclassify the same target again as live on a subsequent glimpse, then another munition gets called in on the same target and the overall number of rounds to kill the targets at the end of the simulation becomes abnormally high. When the "Determine Targets" event iterates through the master target list, if a target is identified as live it will not be available for detection and classification again until after the round designated for it has landed.

2. "Fire At Target" Event

The "Fire At Target" event is simple in what it does, but it is symbolically very important. This event does not take place until after the processing time, which started at detection, has elapsed. Since some of the live targets are movers, there is always a chance that the original target that prompted the firing of a round may not be in the grid when the round lands.

This is the part of the model where timeliness plays its role. The actual values used for the level of timeliness in the model come from a normal distribution with parameters listed in the following table:

Table 5. Timeliness Levels

	High	Medium	Low
mean	10 sec	30 sec	60 sec
std dev	1 sec	3 sec	6 sec

The parameters passed in from the "Determine Targets" event, the target and UAV location, are simply carried

along and passed on to the next event. The “Fire At Target” event does not do anything with these parameters. The purpose of this event is to record the expenditure of a munition and immediately schedule an “Assess Target Damage” event. Technically there would be a time of flight for the round that would take place after the firing event. However, that time is accounted for as one of the components of the aggregated total processing time leading up to the “Fire At Target” event. Therefore the “Assess Target Damage” event is immediately scheduled with a delay of 0.0 seconds.

3. “Assess Target Damage” Event

At this point the munition that was scheduled to be fired (when a target was perceived live back in the “Determine Targets” event) is now about to land. The target that was passed in to this event as a parameter from the “Fire At Target” event is now placed back in the master target list.

a. Target Movement

As in the “Determine Targets” event, moving target locations must be updated. This happens right before the strike of the round and right after the target triggering the firing event is placed back in the master target list. This gives the target that has been held out of the list a chance to update its location before the round selects a target.

b. Target Selection

The UAV parameter that gets passed in to this event contains the grid location of the UAV when the original target was detected and classified. The target

list is iterated through and a new candidate list is built consisting of targets that are currently located in the grid. The candidate list is then iterated through in order to find the original target. If the original target is found then that is the target the round hits. If the original target is not found, but there are other targets in the candidate list, then a target is randomly chosen from the list to be hit by the round. Once a target is taken from the candidate list to be hit by the round, all other targets are returned to the master target list. If no targets are in the candidate list, then the round becomes wasted.

There are a few important notes regarding the accuracy of the munition. As depicted in figure 9, it is envisioned that Objective Force units conducting beyond line of sight (BLOS) fire missions will be utilizing an extended-range precision-guided munition effective out to 12 kilometers.[16] Since the MCS Company in the simulation model is conducting BLOS fire missions at maximum ranges from 8-12 kilometers, when a round is fired into a grid it will kill any target in that grid with a probability of 1.0. This seems consistent with the technical vision for BLOS munition capability in the Objective Force.

[16] National Defense Industrial Association 2001 Munitions Executive Summit 10-12.

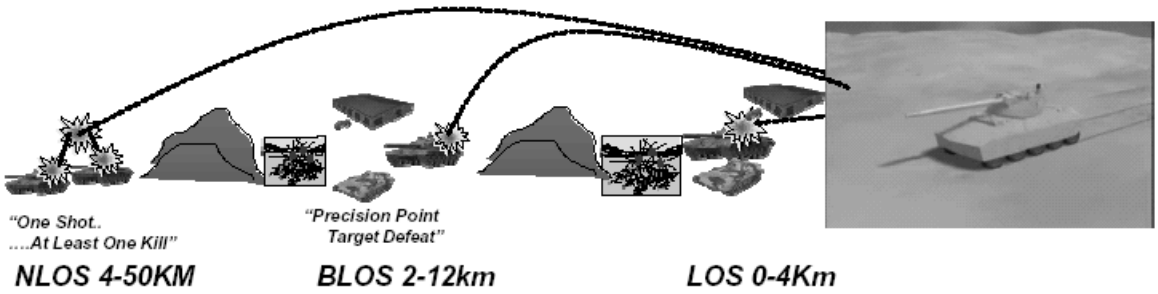


Figure 9. Objective Force Fire Missions

As a convention in the MCSKM, the BLOS round will always seek first the target it was aimed at and kill it if present. However, if the original target is not in the grid the round will randomly choose another target in the same grid and kill it.

If the target chosen by the round is actually already dead or a decoy, even though it was perceived live, that target is simply returned to the master target list and available for detection again. If the target chosen by the round is actually live, then that target is passed as a parameter to the "Change Target State" event with a delay of 0.0 seconds.

4. "Change Target State" Event

The "Change Target State" event makes some changes to the Target object that is passed in. First it changes the target state from live to dead. Then, in case the target was a mover, it ensures that the moving attribute is set to false. Finally, the number of live targets remaining is decreased by one. It is at this event that the MCSKM terminates once the pre-established threshold for the number of killed targets is met.

5. MOE Explanation

When it comes to resource allocation, there is a tension between effectiveness and efficiency.[17] The mission must get accomplished so effectiveness is of primary importance. However, if there are multiple ways of accomplishing the mission, the most efficient one with regards to expenditure of resources is preferred.

By design, the MCSKM will eventually accomplish the mission. Since all targets are at standoff ranges, there is no threat of return fire. If the model runs long enough, no matter how bad the information quality is, the MCS Company will eventually get the enemy down to the desired attrition level. Therefore, the question becomes how efficiently this can be done. That is why the number of munitions fired is the chosen measure of effectiveness (MOE) to determine the relative importance of information timeliness, accuracy, and completeness for this simulation.

[17] FM 6-0, p. 2-26

III. SIMULATION RESULTS AND ANALYSIS

A. EXPERIMENTAL DESIGN

The experimental design implemented for analysis of the Mounted Combat System Killing Machine (MCSKM) is a 3^k factorial design, with k set at 3, meaning there are 3 factors under observation each at three levels.[18] In this case, the three factors are timeliness, accuracy and completeness. The levels for each factor are represented by coded variables as such: high = 1, medium = 0, low = -1. With three factors at three levels each, there are a total of 27 design points. The following table displays the complete design:

Table 6. 3^3 Factorial Experimental Design

Design Point	Completeness level	Accuracy level	Timeliness level
1	1	1	1
2	1	1	0
3	1	1	-1
4	1	0	1
5	1	0	0
6	1	0	-1
7	1	-1	1
8	1	-1	0
9	1	-1	-1
10	0	1	1
11	0	1	0
12	0	1	-1
13	0	0	1
14	0	0	0
15	0	0	-1
16	0	-1	1
17	0	-1	0
18	0	-1	-1
19	-1	1	1
20	-1	1	0
21	-1	1	-1
22	-1	0	1
23	-1	0	0
24	-1	0	-1
25	-1	-1	1
26	-1	-1	0
27	-1	-1	-1

[18] Montgomery, p. 281

The tables below show specifically what values are used for each of the three factors and their three levels:

Table 7. Actual Values for Timeliness

	High(+1)	Medium(0)	Low(-1)
mean	10 sec	30 sec	60 sec
std dev	1 sec	3 sec	6 sec

Table 8. Actual Values for Completeness

	High(+1)	Medium(0)	Low(-1)
UAV Speed	120 km/h	60 km/h	30 km/h
Grid Size	400m	200m	100m

Table 9. Actual Values for Accuracy

	probability of classification (perceived | actual)	High(+1)	Medium(0)	Low(-1)
Live	p(live | live)	0.8	0.6	0.4
	p(dead | live)	0.1	0.2	0.3
	p(decoy | live)	0.1	0.2	0.3
Dead	p(live | dead)	0.1	0.2	0.3
	p(dead | dead)	0.8	0.6	0.4
	p(decoy | dead)	0.1	0.2	0.3
Decoy	p(live | decoy)	0.1	0.2	0.3
	p(dead | decoy)	0.1	0.2	0.3
	p(decoy | decoy)	0.8	0.6	0.6

B. EXPERIMENT RESULTS

For the run of the full experiment, input parameter values were used that correspond to the three levels of timeliness, accuracy, and completeness given in the tables above. The individual parameters were changed in groups, as opposed to individually, based on how each of the three main factors have been defined for this research. Each design point represents a unique combination of factor settings. The response for each design point represents

the number of munitions fired from the entire collection of MCS weapon platforms to kill 80% of the live targets. For each design point 100 replications of the MCSKM were run and the mean response for each design point is listed in the table below:

Table 10. Experiment Summary with Means

Design Point	Completeness level	Accuracy level	Timeliness level	Munitions
1	1	1	1	71.23
2	1	1	0	81.33
3	1	1	-1	99.92
4	1	0	1	106.38
5	1	0	0	112.72
6	1	0	-1	133.88
7	1	-1	1	143.23
8	1	-1	0	156.94
9	1	-1	-1	170.57
10	0	1	1	81.6
11	0	1	0	137.01
12	0	1	-1	142.16
13	0	0	1	121.23
14	0	0	0	188.77
15	0	0	-1	204.82
16	0	-1	1	161.13
17	0	-1	0	251.8
18	0	-1	-1	248.87
19	-1	1	1	104.42
20	-1	1	0	209.87
21	-1	1	-1	201.38
22	-1	0	1	154.83
23	-1	0	0	279.99
24	-1	0	-1	284.39
25	-1	-1	1	214.07
26	-1	-1	0	382.96
27	-1	-1	-1	346.58

1. Model Verification

At a glance, the results seem to meet some common-sense expectations. The high level settings for each of timeliness, accuracy and completeness produce the best MOE

of 71.23 munitions. Likewise, the low level settings for each of timeliness, accuracy and completeness produce nearly the worst MOE of 346.58 munitions. The table below shows the mean responses for all factor levels, evaluated one factor at a time:

Table 11. Mean Responses for each Factor

Timeliness	mean
1	128.68
0	200.15
-1	203.62

Accuracy	mean
1	125.44
0	176.33
-1	230.68

Completeness	mean
1	119.58
0	170.82
-1	242.05

Again, intuition is confirmed by the above results. One would expect the MOE to get worse as the level settings for each factor vary from high to low. According to Law and Kelton, an indicator that a simulation is working properly is that it produces reasonable output when run under a variety of settings of the input parameters.[19]

There is ample evidence to suggest that the MCSKM works properly. As described above, the results meet a basic level of validity as far as the directional effects one would expect to see given the different parameter settings. Also, a detailed trace on the execution of the model was conducted by the author, stepping through the MCSKM event by event. All locations were plotted by hand and state variables were tracked externally to the simulation. Finally, subject matter experts at TRAC-Monterey concurred with the results and agreed they were consistent with the parameter settings chosen.

[19] Law & Kelton, p. 270

2. Determining Factor Significance

With a model that has produced some meaningful output, the task becomes determining the significance of the information quality components. How important is each factor and how much does each factor influence the number of munitions fired?

a. Analysis of Variance

The first step in answering these questions is to look at the results of a three-factor analysis of variance (ANOVA). The table below (computed in the S-PLUS statistical software package) displays timeliness, accuracy and completeness as the sources of variation along with all possible interactions:

Table 12. Analysis of Variance for MCSKM Munitions Fired

Source of Variation	Degress of Freedom	Sum of Squares	Mean Square	F Value	P Value
Completeness	2	6810180	3405090	1761.3	0.0000
Accuracy	2	4986478	2493239	1289.6	0.0000
Timeliness	2	3220931	1610465	833.0	0.0000
Completeness:Accuracy	4	374358	93589	48.4	0.0000
Completeness:Timeliness	4	1230365	307591	159.1	0.0000
Accuracy:Timeliness	4	112753	28188	14.6	0.0000
Completeness:Accuracy:Timeliness	8	56096	7012	3.6	0.0003
Residuals	2673	5167669	1933		

It can be seen that all factors and interactions are statistically significant even at the α=.001 level. In other words, all sources of variation listed above affect the number of munitions fired.

b. Polynomial Regression

Even though all factors and interactions are significant, there is still no indication of their relative

importance in determining the number of munitions fired. In order to gain insight into this aspect of the analysis, a complete second order regression model was fit to the data. The two-way interactions are important in order to gain insight about how factor combinations perform. The squared terms are important to have in the model in order to check for non-linear factor behavior. The value used for each factor was the number corresponding to the level setting (1, 0, -1) instead of the actual value used in the simulation. All replications were used in building the regression model. There are 27 design points and 100 replications for each design point for a total of 2700 data points. The regression model was fit using Excel's regression feature and the results are detailed in table 13 below:

Table 13. Polynomial Regression Model of MCSKM Response

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.85
R Square	**0.73**
Adjusted R Square	0.73
Standard Error	46.88
Observations	2700

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	9	16047867.76	1783096.42	811.46	0.00
Residual	2690	5910962.58	2197.38		
Total	2699	21958830.35			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	192.34	2.39	80.58	0.00	187.66	197.02
Completeness	-61.24	1.10	-55.43	0.00	-63.40	-59.07
Accuracy	-52.62	1.10	-47.63	0.00	-54.79	-50.46
Timeliness	-37.47	1.10	-33.91	0.00	-39.64	-35.30
Completeness^2	10.00	1.91	5.22	0.00	6.24	13.75
Accuracy^2	1.73	1.91	0.90	0.37	-2.03	5.48
Timeliness^2	-34.01	1.91	-17.77	0.00	-37.76	-30.25
Completeness:Accuracy	17.47	1.35	12.91	0.00	14.82	20.13
Completeness:Timeliness	22.96	1.35	16.97	0.00	20.30	25.61
Accuracy:Timeliness	5.12	1.35	3.78	0.00	2.46	7.77

The intercept alone represents the predicted response when all levels are at their medium level (0). The other terms in the model come into play when the level of a factor changes to high (+1) or low(-1). With an R-Square value of .731, this regression model accounts for a significant amount of the variation in the MCSKM output data. The graphs below depict the relationship between the regression model predictions and the actual simulation responses as well as demonstrate the constant variance in the residuals:

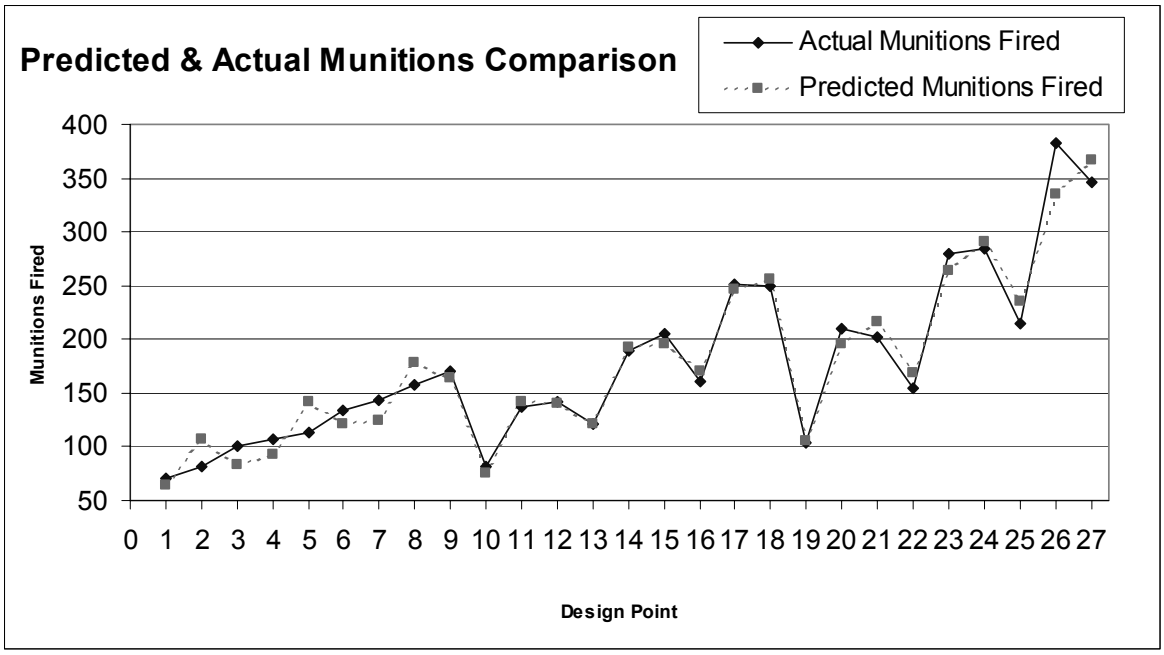


Figure 10. Predicted & Actual Munitions Comparison

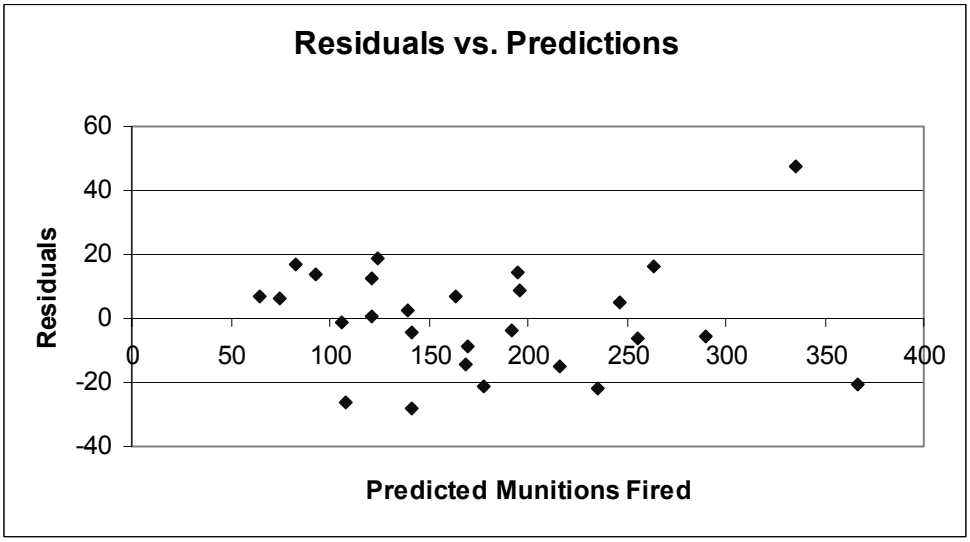


Figure 11. Residuals vs. Predictions of Munitions Fired

Since the polynomial regression model captures the essence of the simulation model output, we can use the

regression model to make some general observations about the way timeliness, accuracy, and completeness behave in this simulation.

All terms in the regression model are significant at the α=0.001 level except for the [accuracy]^2 term. Not only is the p-value for [accuracy]^2 large, but the coefficient is quite small so it has little impact on the response. These two things are indicators that the effect of accuracy on the response is essentially linear according to our coding.

However, the effects of timeliness and completeness are not linear. First, consider what happens to the response when all factors are at the medium level and timeliness alone is varied. These changes are reflected in table 14 below:

Table 14. Changing Timeliness Alone from Medium Level

	Intercept	Completeness	Accuracy	*Timeliness*	C^2	A^2	T^2	CA	CT	AT	Munitions	
settings:		*0*	*0*	*1*	*0*	*0*	*1*	*0*	*0*	*0*		High
values:	**192.3**			**-37.5**			**-34**				**=120.8**	
settings:		*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*		Medium
values:	**192.3**										**=192.3**	
settings:		*0*	*0*	*-1*	*0*	*0*	*1*	*0*	*0*	*0*		Low
values:	**192.3**			**+37.5**			**-34**				**=195.8**	

If timeliness is increased to its high level (setting of 1) the number of munitions goes down by 71.5 (-37.5 – 34) munitions. But if the level of timeliness is decreased to its low level (setting of –1) the number of munitions goes up by only 3.5 (37.5 –34). This is clearly not linear behavior and having the squared term in the regression model captures this dynamic. The bigger resulting change from the medium setting is in the

direction of *decreasing* the number of munitions fired in spite of the fact that going from the middle level to the high level (30 sec to 10 sec) is a shorter step than going from the middle level to the low level (30 sec to 60 sec).

On the other hand, the same procedure applied to the completeness factor indicates the opposite effect. Table 15 below shows what happens when completeness levels are changed in both directions from the medium level:

Table 15. Changing Completeness Alone from Medium Level

	Intercept	*Completeness*	Accuracy	Timeliness	C^2	A^2	T^2	CA	CT	AT	Munitions	
settings:		*1*	*0*	*0*	*1*	*0*	*0*	*0*	*0*	*0*		High
values:	**192.3**	**-61.2**			**10.0**						**=141.1**	
settings:		*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*		Medium
values:	**192.3**										**=192.3**	
settings:		*-1*	*0*	*0*	*1*	*0*	*0*	*0*	*0*	*0*		Low
values:	**192.3**	**61.2**			**10.0**						**=263.5**	

If completeness is increased to its high level (setting of 1) the number of munitions goes down by 51.2 (-61.2 + 10.0) munitions. But if the level of completeness is decreased to its low level (setting of –1) the number of munitions goes up by 71.2 (61.2 + 10.0). This is clearly not linear behavior. However, the bigger change from the medium level setting is in the direction of *increasing* the number of munitions fired in spite of the fact that going from the middle level to the low level 200m grid to 100m grid) is a shorter step than going from the middle level to the high level (200m grid to 400m grid).

By contrast, since the $[\text{accuracy}]^2$ term coefficient is so small (1.7), it would have little effect on the linearity of accuracy if we applied the same

procedure again. The response would essentially change by ± 52.6 rounds, the accuracy term coefficient, which is linear behavior.

These findings can help prioritize the expenditure of resources based on different goals. If the intent is to guard against losing capability, the area of information completeness should be a maintenance priority since this analysis suggests a small drop in this factor level translates into accelerated degradation in munition expenditure efficiency. However, if the intent is to increase the current capability, the area of information timeliness should be a research and development priority since this analysis suggests a small increase in this factor level translates into accelerated improvement in munition expenditure efficiency.

c. Correlation and R-Square Contribution

As mentioned earlier, the polynomial regression model accounts for 73% of the variability in the MCSKM output based on the R-Square value. If we look at the component breakdown of this 73% by how much each term in the regression equation contributes, we can obtain an indication of the relative importance of timeliness, accuracy, and completeness.

In a designed experiment like this one, the coefficients of the terms in the regression model will be uncorrelated (as displayed in figure 11). Therefore, we can actually compute the specific amount of the total R-Square value for which each term is responsible.[20]

[20] Neter

The first step is to compute the correlation of munitions expended with every other term in the model. This can be done by extracting the last row of the correlation matrix produced by Excel:

	Completeness	Accuracy	Timeliness	C^2	A^2	T^2	CA	CT	AT	Munitions
Completeness	1									
Accuracy	0	1								
Timeliness	0	0	1							
Completeness^2	5E-18	-8E-18	-4E-19	1						
Accuracy^2	-8E-18	-8E-18	-4E-19	-3E-18	1					
Timeliness^2	-4E-19	-4E-19	-4E-19	-2E-17	-2E-17	1				
Completeness:Accuracy	0	0	0	-7E-18	-7E-18	5E-19	1			
Completeness:Timeliness	0	0	0	5E-19	5E-19	5E-19	0	1		
Accuracy:Timeliness	0	0	0	5E-19	5E-19	5E-19	0	0	1	
Munitions	***-0.554***	***-0.476***	***-0.339***	***0.052***	***0.009***	***-0.178***	***0.129***	***0.170***	***0.038***	1

Figure 12. Correlation Matrix of Regression Model Inputs

The square of the correlation between Munitions and each term in the regression model becomes that term's component contribution to the total R-Square. Table 16 and figure 13 below summarize this relationship:

Table 16. Component Contribution to Total R-Square

Regression Input:	Completeness	Accuracy	Timeliness	C^2	A^2	T^2	CA	CT	AT
Correlation with Munitions:	-0.5544	-0.4764	-0.3392	0.0522	0.0090	-0.1778	0.1292	0.1697	0.0378
R-Square Contribution:	0.3074	0.2270	0.1151	0.0027	0.0001	0.0316	0.0167	0.0288	0.0014
Total R-Square:	**0.7308**	(sum of above row)							

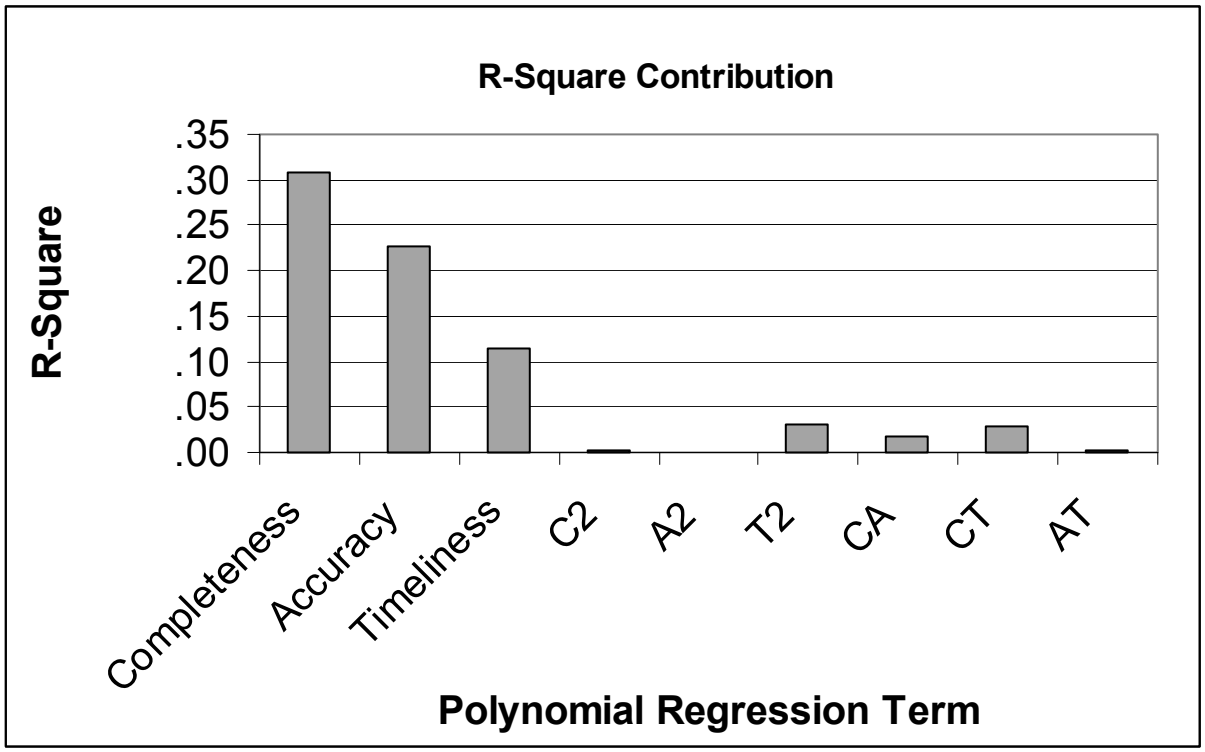


Figure 13. Regression Term R-Square Contribution Chart

Table 17 below displays the percentage of the total R-Square for which each term is responsible. The term that explains the most variability in the number of munitions fired is completeness at 42%. Accuracy and timeliness follow at 31% and 16% respectively. $[Timeliness]^2$ as well as the two interactions of completeness:accuracy and completeness:timeliness explain roughly 2-4% of the variability each.

Table 17. Percentage of Total R-Square Contribution

Regression Input:	**Completeness**	**Accuracy**	**Timeliness**	**C^2**	**A^2**	**T^2**	**CA**	**CT**	**AT**
R-Square Contribution:	0.3074	0.2270	0.1151	0.0027	0.0001	0.0316	0.0167	0.0288	0.0014
Percentage of Total R-Square:	**42.06%**	**31.06%**	**15.75%**	**0.37%**	**0.01%**	**4.32%**	**2.28%**	**3.94%**	**0.20%**

3. Summary

The analysis above of the MCSKM output shows several things. From the analysis of variance it can be seen that the three factors of timeliness, accuracy and completeness as well as their two-way interactions are significant. In other words, each factor has a unique impact on the number of munitions fired. No two factors are interchangeable.

Building a complete second order regression model that fits the MCSKM output reasonably well provides a framework to look at the relative significance of the terms used to build the model. The coefficients on the squared terms provide an indication of the linearity of the three factors. The size of the coefficient on the squared term provides an indication of the degree of non-linearity that exists with regards to that factor. The sign of the coefficient is an indicator of which direction of travel from the medium setting provides the bigger change in the number of munitions. A positive sign on the coefficient of the squared term indicates that the number of rounds changes more as the level of the main factor goes down. A negative sign on the coefficient of the squared term indicates that the number of rounds changes more as the level of the main factor goes up.

The regression model also indicates there exists a beneficial timeliness:accuracy interaction when each of these factors is set at its high level. Figure 14 below demonstrates that the model's top three predictions all occur when timeliness = accuracy = +1.

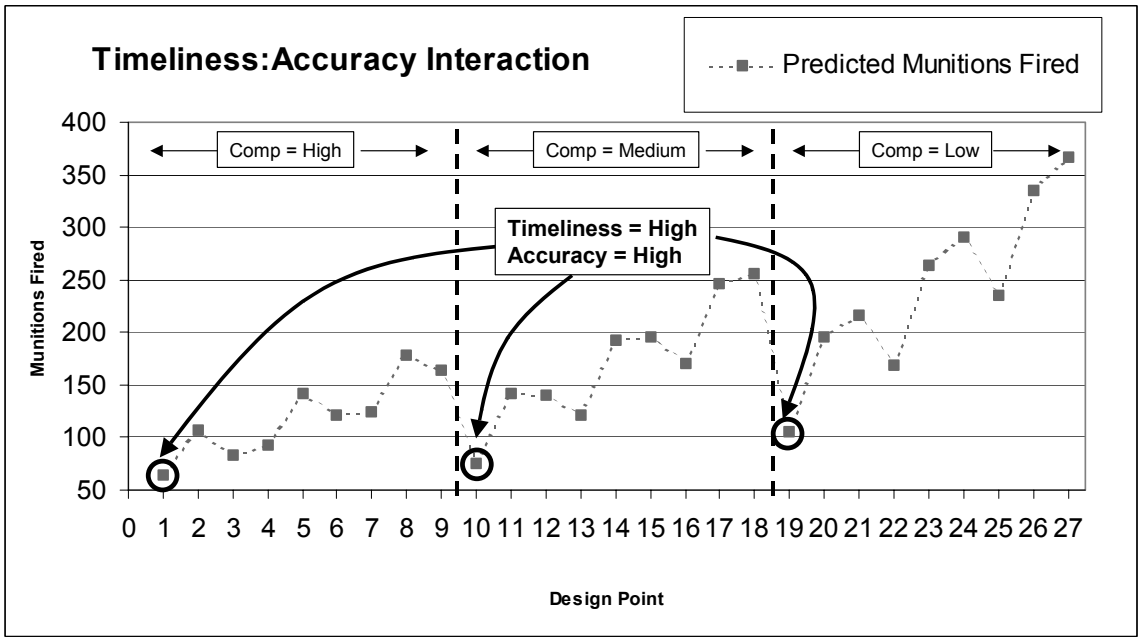


Figure 14. Regression Model Top Predictions

A beneficial timeliness:accuracy interaction is further evidenced by the fact that three of the top five MOE values resulting from the actual simulation runs (refer back to table 10) are at design points 1, 10, and 19, where timeliness and accuracy are each at their high level. Therefore, while at their high levels, the interaction of timeliness and accuracy negates the contribution of completeness.

Finally, the correlation of Munitions to the other terms in the regression equation provides a way to get at the component pieces of the total R-Square value. This gives a good indication of the impact of each term's influence on the number of munitions fired.

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IV. CONCLUSIONS

A. INFORMATION QUALITY COMPONENT IMPACT

The goal of this thesis was to draw some broad conclusions about how the individual components of information quality can influence combat outcomes. It turns out that information timeliness, accuracy and completeness each have a distinctive and significant impact on the results of a combat scenario.

1. Simulation Results Implications

In this scenario we were able to see that varying the levels of these components affect the number of munitions required to kill a given percentage of enemy targets. Although the output of the MCSKM is heavily dependent upon the scenario, the MOE, and input data, we discovered that that the individual effect of timeliness, accuracy and completeness may not be linear. Knowing where and how to achieve an accelerated return based on an incremental change to any of these components is important. We also discovered in this analysis that there are significant synergistic effects that take place between information components. Knowing that the combined effects of two of these components can overshadow the effect of the remaining component is important as well.

The dynamic relationship among information quality components that emerged from this analysis is likely to exist in virtually any given scenario and the particulars of that relationship will be unique to that scenario. This information in the hands of a concept developer allows him to make wise choices in determining what technologies and

tactics are needed to improve the success of units optimized for specific missions.

2. Insights Gained from Preliminary Experimentation

Although the MCSKM has the ability to represent a wide variety of parameters, many were held fixed in this analysis. The fact that many of the parameters were not varied suggests much future work that will be addressed in the next section. However, below are just a few insights gained from trial and error:

a. Magnification of Small Performance Errors

With a probability of false detection and a probability of detection being varied as part of the accuracy component, the round counts were ranging from approximately 300 with factors at the high levels to 14,000 with factors at the low levels. The UAV can make a false detection at every glimpse. In the course of an entire run of a scenario there are so many glimpses that even if the probability of false detection is as small as .01 there could be hundreds of false detections each resulting in a wasted round.

The probability of detection compounded this problem by dragging out the simulation. If a target was present in the grid but not detected, the UAV would pass over it and have to randomly come back to it at a later time. By the time the UAV comes back to the target it has had numerous opportunities to make false detections, misclassify dead or decoy targets as live, and waste more rounds.

The attrition level was yet another contributor to the problem. After the majority of the live targets are

found and killed, the UAV has to keep looking for the last few live targets and spends a lot of time wasting rounds in the meantime.

In order to keep the number of munitions at a reasonable level, reduction of the complexity of the accuracy component was necessary. This was achieved by taking the effect of false targets and the probability of detection out of the scenario. The probability of classification alone produced more interpretable results.

After the accuracy component was brought under control, the attrition level was less influential in high round counts. However, keeping the attrition level at 80% provided a stopping criteria that allowed the simulation to run in a reasonable amount of time (which is important for multiple runs). The scenario chosen for this analysis suggested the 80% attrition factor.

The insight gained from all of this was that imperfect information results in substantial inefficiencies in destroying targets and even small performance errors become magnified over the course of a lengthy engagement.

b. Completeness of Information Depends on Time

Initially the completeness component of information was modeled strictly by the size of the grid square representing the footprint of the UAV's sensor. However, the results from these simulation runs did not make much intuitive sense. It became apparent that a UAV could look at four 100m by 100m grid squares in the same amount of time it could look at one 200m by 200m grid square. This happened because the UAV traveled at a fixed speed and the time in the grid square was adjusted at each

completeness level to account for this. In other words, for any given block of time the same amount of area on the ground was potentially covered regardless of the completeness setting.

As a reminder, completeness describes the level to which all the relevant items of information are available. Since target information was the relevant item in this scenario, the piece of information that contained data on the most number of targets was the most complete. To model completeness more appropriately, the levels were redefined so that time in the grid square was held fixed and the size of the grid square changed. This required UAV speed (which was previously held constant) to vary in conjunction with the grid size.

B. FUTURE STUDY RECOMMENDATIONS

A more comprehensive understanding of the impact of information on combat outcomes requires further research in several areas. Some logical ways to proceed from this research are listed below.

1. Refine the Parameters Associated with Timeliness, Accuracy and Completeness

It was difficult to come up with just the right way to model the components of information quality. There are other variables that could be associated with each component. Choosing these variables, as well as the appropriate levels for each, and then relating them the proper way would improve the quality of the response and provide further insights into the dynamics of how these information quality components relate to each other and to the combat outcome.

2. Apply Analysis Framework to Other Scenarios

The MCSKM is adaptable to explore many other scenarios. This can be done by modifying the objective area size and shape, number of UAVs used, distributions used for the varying parameters, number and types of targets, and input values for parameters. Scenarios could be compared with one another to make observations about how the relationship among timeliness, accuracy and completeness may differ.

3. Multiple UAV Types

Although the MCSKM is currently capable of portraying a variable number of UAVs, they all have the same characteristics. Modifying the MCSKM to allow for multiple types of UAVs would facilitate the exploration of a wider variety of scenarios and provide interoperability with existing and future sensor mix optimization models.

4. Complementary Study on the Value of Information

Information can be broken down into two attributes: value and quality. The focus of this thesis was on information quality in terms of timeliness, accuracy and completeness. A study on the value of information would provide additional insights into how information affects combat outcomes and, combined with this study, provide a more consummate interpretation of the overall impact of information.

5. Spreadsheet Version of MCSKM

Although the MCSKM is written in Java as a discrete-event simulation, a spreadsheet implementation of the basic concepts behind the MCSKM does exist. The spreadsheet version provides an easier and more familiar environment

for anyone interested in examining the underlying relationships in the MCSKM. However, the spreadsheet version in its current state lacks several parameters found in the MCSKM and is not generalized enough to make it extensible for other scenarios.

The Java source code for the MCSKM and the Excel file containing the spreadsheet implementation discussed above are both available by contacting MAJ Joseph Baird, United States Military Academy, Department of Mathematical Sciences, West Point, New York.

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Department of Mathematical Sciences
United States Military Academy
West Point, NY